Integrating Environmental Impacts as another Measure of Earthquake Performance for Tall Buildings in High Seismic Zones

K. Simonen[1], S. Merrifield[2], I. Almufti[3], K. Strobel[4], J. Tipler[5]

[1]Associate Professor, Department of Architecture, University of Washington, Box 355720 Seattle, WA 98195-5720, 206-685-7282, ksimonen@uw.edu
[2]Engineer, Arup, 560 Mission Street, San Francisco, CA 94105, 415-957-9445, sean.merrifield@arup.com
[3] Associate, Arup, ibrahim.almufti@arup.com
[4] MArch and MS Student, University of Washington, Seattle, WA, strobelk@uw.edu
[5] MS Student, Stanford University, Palo Alto, CA, jtipler@stanford.edu

ABSTRACT

This study assesses the environmental impacts of an archetypical contemporary 42-story residential concrete building designed to meet minimum code requirements and compares it to the impacts from a "beyond code" design. The earthquake performance of the building in terms of financial loss and repair time was previously evaluated using a FEMA P-58 based approach; this research used Life Cycle Assessment to estimate the environmental impact of both initial construction and seismic repair when the building is subjected to an earthquake with a 475-year return period. Three seismic force resisting configurations (fixed-base, base-isolated, and damped-outrigger) as well as two design approaches (minimum code equivalence and a resilience-based design approach) were considered. This study found that the magnitude of environmental impact of seismic damage repair can be significant; that the ratio of environmental impact to cost is higher for seismic repair than initial construction; and that the protection of non-structural components, such as partitions, can result in significant reduction in overall environmental impact of seismic damage when subjected to large earthquakes.

INTRODUCTION

The primary aim of this study is to examine the feasibility of integrating variables which describe the environmental impacts of earthquake damage within existing performance-based assessment methods.

An archetypical contemporary 42-story reinforced concrete core wall residential building was developed as part of separate study (Almufti et al., 2015). Three separate structural schemes were considered (fixed-base, base-isolated, and damped-outrigger systems), all following traditional performance-based design guidelines to represent state-of-the-art practice for tall buildings designed to modern building code standards. In addition, enhanced non-structural detailing per the REDi 2013 guidelines was also considered for each structural scheme to investigate the cost-benefit of implementing enhanced detailing. The type and extent of damage to all building components (including structure, cladding, building systems, and architectural fit-out) and the corresponding repair costs under the 475-year return period earthquake was evaluated using the Performance Assessment Calculation Tool or PACT (FEMA, 2012b)

Environmental Life Cycle Assessment (LCA) was used to estimate the environmental impact of both the initial construction and the repair. Economic Input-Output LCA (EIO-LCA) data (CMU GDI, 2014) correlates dollars spent in a specific industrial sector to environmental impacts. Multiple primary environmental impact indicators were assessed both individually and collectively to determine a single performance 'score.' This paper provides an overview of the analysis process and an evaluation of the results relevant to those looking to better understand the seismic performance of high-rise residential towers and the environmental impact of seismic damage.

LCA Background

LCA is a method of quantifying the environmental impact of a product or process either for a specific life cycle stage (e.g. manufacturing) or over the full life cycle (e.g. cradle-to-grave). Although the methods of LCA are standardized (ISO, 2006a&b), the details of conducting a life cycle assessment study are flexible and need be clearly defined as part of the LCA documentation. Per ISO standards, the LCA report must explicitly include the following components: the goal and scope of the study, the inventory method, the impact assessment method and an assessment of the results.

Life Cycle Inventory (LCI) datasets that attribute emissions to air and water (e.g. CO_2 or methane) to specific processes (e.g. combustion of coal in an industrial boiler or manufacturing of a kg of cement) or to dollars spent in a specific industrial sector (e.g. lime and gypsum product manufacturing or flat glass manufacturing) exist. LCAs developed from process based LCIs are used in building industry specific tools such as Athena (Athena, 2014) and Tally (KT Innovations, 2014) and are sometimes termed 'process based LCA'. EIO-LCA (CMU GDI, 2014) LCI data is developed by connecting economic and environmental data submitted to the government from industry. Environmental impacts are reported based upon dollars spent in specific industrial sectors (e.g. lime and gypsum product manufacturing). In cases (such as this one) where detailed material quantities are not known but detailed cost information is available, EIO-LCA enables a comprehensive LCA without requiring the time consuming and uncertain effort of extrapolating material quantities from the cost data.

The US Environmental Protection Agency has published characterization factors that enable the compilation of many chemical emissions into representative environmental impacts for the United States (TRACI, 2012). LCA is most effective in reporting environmental impacts that are related to emissions from energy generation. Some, but not all, of the process based chemical reaction emissions are included in LCIs and the impacts of material use, maintenance and end of life are not always known and/or are difficult to model effectively. Additional environmental impacts such as those related to resource extraction, habitat protection and water quality are not well captured by LCA and are not included in this analysis.

Literature Review

In order to help owners and policy makers understand the true life cycle costs of their decisions when evaluating uncertain, but likely, events such as earthquakes, methods to integrate probabilistic analysis were developed. Performance Based Seismic Design (PBSD) has evolved over the past decades from initial concepts (Krawinker et al, 2006) to include specific performance assessment methodology such as FEMA P-58-1 (FEMA, 2012a) as implemented into the assessment tool PACT (FEMA, 2012b).

Typical LCA does not include hazard assessment yet hazard resistance has been shown to be important to study (Plublee and Klotz, 2014 & Sarkasian et al., 2014). There is a growing body of research attempting to integrate environmental assessment and seismic performance evaluation. The research presented here builds directly upon research funded by FEMA to develop methods to integrate Life Cycle Assessment (LCA) based environmental impacts into the seismic performance assessment methodology (FEMA, 2012c). Some similar research uses HAZUS to assess environmental impacts (Feese et al, 2014 and Comber et al., 2012). Others use similar probabilistic analysis and process based LCA but do not include comprehensive assessment of the non-structural components (Menna et al., 2012, Hossain and Gencurk, 2014, Chiu et al., 2012).

This research is unique in that it includes a comprehensive seismic performance evaluation (including both structural and non-structural components), evaluates multiple design iterations to enable a cost-benefit study, and incorporates an environmental assessment of both the initial construction and the damage by using an EIO-LCA to estimate relative environmental impacts.

METHODS

Summary of PBSD Case Study Building

A theoretical 42-story residential building, located in San Francisco, California, was considered. This same archetype building is studied in Almufti et al.

(2015) which was based on a study by PEER (2012). A rendering of the building, as well as the typical floor plan, is shown on Figure 1.

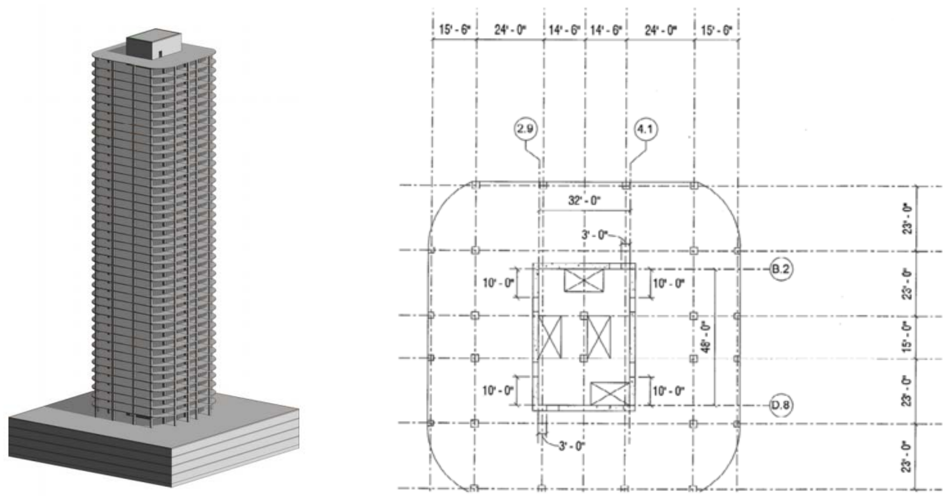

Figure 1. Case study building elevation (left) and typical structural floor plan (right)

The case study building has a 42-story superstructure that sits on a 4-story basement structure. The building's mat foundation consists of 36, 6-foot diameter piles, 125' in length. The 4 basement levels are assumed to be used for parking, while the superstructure floors are typically residential, with the exception of the roof penthouse, which is used a mechanical room. The floor height of the structure is 10' for the basement levels, 12' 6" for Level 1, 9' 8" for the 41 residential levels, and 10' 8" for the roof penthouse.

Three different structural systems were considered: fixed-based, damped-outrigger, and base-isolated, designed by Almufti, et al. (2015). The lateral system for the fixed-base structure is a concrete core wall with coupling beams, in which the energy dissipation is provided by flexural yielding of the coupling beams and at the base of the core wall. The damped-outrigger design is similar to the fixed-base case, but an outrigger system is incorporated at mid-height of the building, which uses linear viscous dampers connected between the core wall outrigger and perimeter gravity columns. The base-isolated design uses triple-friction-pendulum bearing isolators, with an isolation plane located at ground level.

Two types of design were considered for each structural system. The first type reflects the current state-of-practice for tall buildings under the PEER TBI guidelines, where the building is designed to remain elastic under the service-level earthquake hazard, and nonlinear time history analysis (NLTHA) is used to verify that a 'collapse-prevention' performance level is achieved at the Maximum Considered Earthquake (MCE) hazard level (typically a return period of 2475 years). The second design type follows the Resilient Earthquake Design Initiative (REDi™) guideline principals, which has enhanced seismic performance objectives to reach a 'REDi

Gold' standard. To achieve 'REDi Gold', the structure has to remain essentially elastic at the 475-year hazard level, and non-structural components are detailed such that they can accommodate the drifts and accelerations that are expected. REDi Gold performance is verified when the loss assessments indicate that the building's median financial loss is less than 5% of the initial construction cost, as well as less than 1 month of building downtime. The reader is directed to PEER TBI and REDi™ guidelines for additional information on the two design approaches and Almufti, et al. (2015) for additional information on the case study building designs, dynamic properties, and structural performance under the 475-year hazard level. Estimates of the initial cost of each design is also presented in Table 3 adjacent to the final results.

LCA Summary

The primary goal of this LCA study is to evaluate the environmental impact of both initial construction and seismic damage repair. The environmental impact performance of six designs of the high-rise tower are evaluated and compared in an attempt to develop general recommendations for designers of similar buildings. Additionally, the study tests methodology to integrate LCA and PBSD proposed in FEMA P-58-4 (FEMA, 2012c).

This LCA study focused on the impacts of material manufacturing and transportation of various structural and non-structural components, both during initial construction and due to repairs of seismic damage. As all towers are similar in configuration and use, the operational energy impacts are the same for the different options and were not included in this study. Due to lack of easily available data and time, the construction, maintenance, and end of life impacts are not included. EIO-LCA was used (CMU GDI, 2014) to estimate the environmental impact of initial construction and damage as it resulted in both a more comprehensive analysis and was implementable given the scope of this project. The construction cost estimate was developed to a high level of detail and PACT outputs damage costs per individual component enabling differentiation of costs into specific industrial sectors. The practicality of using process based LCA for this study was tested and rejected for the following reasons: existing whole building LCA tools do not include non-structural components (e.g. elevators or mechanical and electrical equipment); the research team did not have the expertise or resources to estimate the materials used in these components; and for the components tested, the effort extrapolate material quantities used to repair other components and conduct specific LCAs of the different damage state repairs included substantial uncertainty and required more effort than this project could support. Of note, the EIO-LCA dataset uses relatively old (2002) emissions data and does not include uncertainty.

The EPA's TRACI characterization factors (EPA, 2012) were used to report environmental impacts and the Climate Change, Acidification and Eutrophication were tracked. In addition, the National Institute of Standards BEES Stakeholder Scoring method (Lippiatt, 2007) to weight multiple impacts to determine a single 'environmental score.' The BEES 'combined score' includes both environmental and economic impacts. In our example we weighted these 50/50.

Integration of PBSD Output and LCA

The PBSD analysis results from PACT include a detailed reporting of the mean number of components (e.g. curtain wall) damaged as well as the level of damage (DS1=low damage, DS3=high level of damage). Each component included a description of the expected damage and repairs along with an estimate of costs to repair. See Table 1 for a summary of an example user defined case, partitions.

For each of the damaged components, we developed EIO-LCA estimates. Based upon the description of damage and damage cost within each fragility, we estimated how much of the total repair cost should be allocated to each industrial sector as summarized in Table 2. In addition the costs attributed to labor (not considered an environmental impact) were removed, the material costs de-escalated to 2002 data (to align with the EIO dataset), and costs were multiplied by a factor to translate regional data to national average costs (RS MEANS, 2011).

Table 1: Example fragility damage state repair summary and cost.

C1011.001e: USER DEFINED Wall Partition, Type: Gypsum with metal studs, Full Height, Fixed Below, Fixed Above (Racking EDP) 13'x100' panel			
	Description of Damage	**Description of Repairs**	**Cost/ 100'**
DS1	Screws pop-out, minor cracking of wall board, warping or cracking of tape.	Re-tape joints, paste and repaint both sides of full 100 foot length of wall board.	$5,100
DS2	Moderate cracking or crushing of gypsum wall boards (typically in corners and in corners of openings).	Remove full 100 foot length of wall board (both sides), install new wall board (both sides), tape, paste and repaint.	$19,800
DS3	Significant cracking and/or crushing of gypsum wall boards-buckling of studs and tearing of tracks.	Remove and replace full 100 foot length of metal stud wall, both sides of the gypsum wall board and any embedded utilities, and tape, paste and repaint.	$31,600

The inventory of materials used were calculated as outlined above and the corresponding environmental impacts were attained using data from the Green Design Institute (CMU GDI, 2014) website. The total environmental impact for each damage state of each damaged component was calculated with five typical LCA impacts. See the following section for a summary of the interpretation of LCA.

Table 2: Example EIO-LCA calculation for partition walls.

EIO Sector # & Name		Cost per 100'	% Labor	Material Cost*	Damage State
325510	Paint and Coating Mfg	$1,020	80%	$131	DS1, 2 & 3
3274A0	Lime and Gyp Product Mfg	$4,080	80%	$522	DS1, 2 & 3
3274A0	Lime and Gyp Product Mfg	$13,230	40%	$5,080	DS2 & 3
	Demolition	$1,470	100%	$0	DS2 & 3
332114	Custom Roll Forming	$13,520	40%	$5,192	DS3
	Demolition	$1,690	100%	$0	DS3
335920	Electrical/Plumbing	$1,690	60%	$433	DS3

*Note: Material cost has been deflated to reflect 2002 values and multiplied by a factor to translate regional (Northern California) costs to U.S. National relative values.

RESULTS

The case study building's mean total financial loss under the 475-yr return period earthquake hazard was assessed using PACT in the Almufti, et al. (2015) study. The financial loss results from their study are briefly presented here to highlight the performance of each building configuration, as well as for comparison against associated environmental impacts. Table 4 provides a comparison of median financial losses computed by PACT for each structural system and design type, which can be assessed relative to the costs and environmental impacts of the initial construction. Results are expressed in both USD, as well as a percentage of the initial construction cost. It is evident that the base isolated systems provide the best performance in terms of financial loss mitigation, while the fixed-base PBD design has the greatest financial loss (and also had the lowest initial cost). The REDi damped-outrigger and base-isolated systems provide the greatest reduction in dollar losses in comparison to the fixed-base PBD, but also hold the highest cost premiums in implementing the design. If the effect of the cost premium is factored in by taking the ratio of loss reduction to cost premium, it is evident that the PBD base-isolated design is most efficient, providing roughly 16 dollars of loss savings for every extra dollar spent on the initial design. The REDi base-isolated design is another appealing alternative, providing roughly 9 dollars loss savings for every extra dollar spent.

The environmental impacts of initial construction and repair are shown in Tables 3 and 4. The results are presented in millions of kg $CO2_e$ and a unitless BEES scores. The environmental impact premium of all enhanced performance schemes is quite low (max 1%) while the reduction of seismic repair impact is significant (max 20% of initial construction GHG emissions). Note that the increase in environmental impact from the REDi schemes is calculated based upon the increase in initial construction costs. Based upon the precision of the analysis, one can say that all four schemes are comparable (within 1% of each other in all measures) based upon initial construction alone. Including earthquake repair, the REDi schemes show a significant improvement (14-20%) in total life cycle impacts and both iterations of the base isolated scheme demonstrate at least a 10% improvement.

Table 3. Initial cost and environmental impact for each system/design type.

	Fixed Base		Outrigger		Base Isolated	
	PBD	REDi™	PBD	REDi™	PBD	REDi™
Superstructure Hard Costs	$40.5M	$40.5M	$42.3M	$42.3M	$42.2M	$42.2M
Non-Superstructure Hard Costs	$135M	$137M	$136M	$137M	$136M	$137M
TOTAL HARD COSTS	**$176M**	**$178M**	**$178M**	**$180M**	**$177M**	**$179M**
Cost Premium over Fixed Base PBD	$-	$1.91M	$1.76M	$3.67M	$0.55M	$2.46M
Cost Premium %	-	1.09%	1.00%	2.08%	0.96%	2.05%
TOTAL GHG EMISIONS (kgCO2e)	**103.3M**	**104.1M**	**103.5M**	**104.4M**	**102.8M**	**103.6M**
GHG Premium %	-	1.14%	0.19%	1.06%	-0.48%	0.29%
BEES Environmental Score	3091	3116	3099	3124	3076	3101
BEES Combined Score	98	99	99	100	99	100

Table 4. Median financial loss & environmental impact for each system/type.

	Fixed Base		Outrigger		Base Isolated	
	PBD	REDi™	PBD	REDi™	PBD	REDi™
MEDIAN FINACIAL SEISMIC LOSS	**$26.8 M**	**$14.4M**	**$24.2 M**	**$12.6 M**	**$18.0 M**	**$4.3 M**
% Initial Cost	15%	8%	14%	7%	10%	2%
Loss Reduction per Fixed Base PBD	**$-**	$12.3M	$2.6 M	$14.2 M	$8.7 M	$22.4 M
Ratio: loss reduction to cost premium	-	6.47	1.47	3.86	15.87	9.12
MEDIAN GHG of SEISMIC REPAIR (kgCO2e typ.)	**24.6M**	**10.5M**	**21.7M**	**7.6M**	**16.8M**	**2.4M**
% Initial GHG Emissions	24%	10%	21%	7%	16%	2%
GHG Loss Reduction per Fixed Base PBD	-	14.1M	3.0M	17.1M	7.8M	22.2M
GHG Premium over Fixed Base PBD	-	0.8M	0.3M	1.1M	-0.5M[1]	0.3M
Ratio: loss reduction to GHG premium	-	16.84	11.05	15.45	-15.00[1]	70.46
Initial + Damage BEES Envir.. Score	3850	3442	3767	3358	3593	3176
Initial + Damage BEES Combined Score	100	92	99	91	95	87

[1] Note given lower initial environmental impact of base isolated scheme, any reduction in environmental benefit would be worthwhile.

DISCUSSION & CONCLUSIONS

Based on initial construction, the fixed-base standard building has the lowest economic cost however the base-isolated building has the lowest environmental cost. When you incorporate earthquake damage, the base-isolated REDi building becomes the best option environmentally and economically. The added cost of base isolation does not increase the initial environmental impact of construction due to the reduction of superstructure materials. Base isolating a building of this scale is not common in the United States though it has been done in Japan. All three schemes show a significant environmental improvement when utilizing the REDi system, primarily due to the reduction of damage to partitions. The ratio of loss reduction to environmental cost premium is much greater than dollar cost ratios indicating that those who prioritize reducing the total environmental life cycle impact of buildings should build buildings with high performance. Based upon the BEES combined score (integrating economic and environmental concerns), all REDi™ schemes are of similar rating.

Table 5 outlines the distribution of damage in the different schemes based upon the top ten contributors to damage of the Fixed Based PBD scheme. Of note the impact of partition damage is by far the largest contributor to GHG emissions and this study indicates that protection of partitions should be an area of relatively high priority.

Table 5. Distribution of GHG emissions per component type.

	GHG Emissions of Seismic Damage in 1,000 kg CO2e					
	Fixed Base		Outrigger		Base Isolated	
	PBD	REDi™	PBD	REDi™	PBD	REDi™
Partition Walls	17,115	3,427	16,845	3,020	14,093	69
PT Slab	2,067	2,067	1,779	1,779	504	504
Link Beams	3,842	3,842	1,576	1,576	1,122	1,122
Wall Finish	833	841	833	841	831	528
Curtain Wall	430	-	304	-	44	-
Chiller	163	163	158	158	71	71
Concrete Wall Type A	107	107	104	104	77	77
Concrete Wall Type B	63	63	62	62	49	49
Steel Stair	8	8	7	6	4	3
Elevator	3	-	3	-	0	-
Other	1	1	1	1	0	0

This analysis is completed based a single earthquake hazard level. If the PBSD considered a suite of earthquake hazards and their relative probability of occurrence, the analysis could have resulted in a mean annual predicted economic and environmental cost of seismic damage. However, this would require significant additional analysis time. Without this information, decision makers must internalize this probabilistic risk.

Future research of value includes: the integration of environmental impact into the PACT assessment tool; the assessment of uncertainty in environmental impact (due both to uncertainty in estimating materials/processes as well as the uncertainty in estimating environmental impact for each material/process); comparing the analysis results using process based LCA methods; developing methods to integrate these results into more conventional whole building LCA studies rewarded by green building rating systems; and testing different building types, construction and configuration to evaluate if generalizable recommendations can be made.

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REFERENCES

Almufti, I, Tipler, J., Merrifield, S., Carey, B., Willford, M. and G. Deierlein, (2015: under review). "Performance and Cost Implications of Resilience-based Earthquake Design for Tall Buildings in High Seismic Zones using the REDi™ Rating System," ASCE Special Issue on Resilience-Based Design of Structures and Infrastructure.

Almufti, I and Wilford, M. (2013). "REDi™: Resilience-based Earthquake Design (REDi) Rating System." Accessed December, 19, 2014 from http://www.arup.com/Publications/REDi_Rating_System.aspx.

Athena Sustainable Materials Institute (Athena) (2014) "Athena Impact Estimator for Buildings." Software. Available from www.athenasmi.org.

Chang, Y. S., Cheng, Y. L., Lin, S. T., and Sheu, M. S. (2002). "A simplified evaluation method for the CO2 emission of buildings in Taiwan." *J. Archit*., 41, 1–21.

Chiu, C.K., Chen, M.R., and Chiu, C.H. (2013). "Financial and Environmental Payback Periods of Seismic Retrofit Investments for Reinforced Concrete Buildings Estimated Using a Novel Method." *J. of Architectural Engineering*, 19.2, 112-118.

CMU GDI (Carnegie Mellon University Green Design Institute) (2014). Economic Input-Output Life Cycle Assessment (EIO-LCA) US 2002 (428 sectors) Producer model. www.eiolca.net [Accessed 13 Aug, 2014].

Comber, M.V., Poland, C., and Sinclair, M. (2012). "Environmental Impact Seismic Assessment: Application of Performance-Based Earthquake Engineering Methodologies to Optimize Environmental Performance." *SEI 2012*, 910-21.

EPA (2012). "Tool for the Reduction and Assessment of Chemical and other environmental impacts (TRACI)" U.S. Environmental Protection Agency (EPA). Excel File. TRACI_2_1.xlsx from Jane Bare at EPA bare.jane@epa.gov.

Feese, C., Li, Y., and Bulleit, W.M. (2014). "Assessment of Seismic Damage of Buildings and Related Environmental Impacts." *J. Perform. Constr. Facil.*, 1-10.

FEMA (2012a). "FEMA P-58-1: Seismic Performance Assessment of Buildings Volume 1-Methodology," Federal Emergency Management Agency.

FEMA (2012b), "Seismic Performance Assessment of Buildings,' Software available from http://www.fema.gov/media-library/assets/documents/90380.

FEMA (2012c). "FEMA P-58-4: Seismic Performance Assessment of Buildings Volume 4-Methodolgy for Assessing Environmental Impacts," Federal Emergency Management Agency.

FEMA (2013). HAZUZ Technical Manual. (http://www.fema.gov/media-library-data/20130726-1820-25045-6286/hzmh2_1_eq_tm.pdf

Hossain, K.A., and Gencturk, B. (2014). "Life-Cycle Environmental Impact Assessment of Reinforced Concrete Buildings Subjected to Natural Hazards." *J. Archit. Eng.,* 13.5, 1-12.

Hossaini, N., Reza, B., Akhtar, S., Sadiq, R., and Hewage, K. (2014). "AHP based life cycle sustainability assessment (LCSA) framework: a case study of six story wood frame and concrete frame buildings in Vancouver." *J. of Env. Planning and Management,* 3, 1-25.

International Organization for Standardization (ISO). (2006a) *14040:2006 Life Cycle Assessment--Principles and Framework.* Geneva: ISO.

International Organization for Standardization (ISO). (2006b) *14044:2006 Environmental management-Life cycle assessment-Requirements and guidelines.* Geneva: ISO.

KT Innovations (2014) "Tally Software." Version 2014.12.10.01. Available from www.choosetally.com.

Krawinkler, H., Zareian, F., Medina, R. A., and Ibarra, L.F. (2006). "Decision Support for Conceptual Performance-based Design." *Earthquake Engineering & Structural Dynamics,* 35.1, 115-33.

Lippiatt, B., (2007) “NISTIR 7423: BEES 4.0 Building for Environmental and Economic Sustainability Technical Manual and User Guide,” National Institute of Standards and Technology Administration, U.S. Department of Commerce.

Masanet, E., Stadel, A., and Gursel, P. (2012). “Life-cycle evaluation of concrete building construction as a strategy for sustainable cities.” *SN3119*, Portland Cement Association, Skokie, Il.

Menna, C., Asprone, D., Jalayer, F., Prota, A., and Manfredi, G. (2013). “Assessment of ecological sustainability of a building subjected to potential seismic events during its lifetime.” *Int. J. Life Cycle Assess.,* 18, 504-515.’

RS Means, (2011). *Building Construction Cost Data*. R.S. Means Company.

PEER (2012). Moehle, J., Bozorgnia, Y., Jayaram, N., Jones, P., Rahnama, M., Shome, N., Tuna, Z., Wallace, J., Yang, T., and Farzin Zareian. “Case Studies of the Seismic Performance of Tall Buildings Designed by Alternative Means”, Task 12 Report for the Tall Buildings Initiative, Pacific Engineering Earthquake Research Center.

Plumblee, J., and Klotz, L. (2014). “Marlo’s windows: why it is a mistake to ignore hazard resistance in LCA.” *Int. J. Life Cycle Assess.,* 19, 1173-78.

Sarkisian, M., Brunn, G., Nasr, M., Hachem, M., and Hu, L. (2011). “Predicting the Environmental Impact of Structures in Regions of High Seismic Risk.” *AEI 2011*, 263-271.

Simonen, K. (2012) *Life Cycle Assessment (Pocket Architecture),* Routledge, London, U.K.

UNEP (2007) *Montreal Protocol on Substances that Deplete the Ozone Layer 2007: A success in the Making,* United Nations Ozone Secretariat. Accessed January 15, 2015 from http://ozone.unep.org/Publications/MP_A_Success_in_the_making-E.pdf.